[redacted]

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GNE/ENP/90M-6

EVALUATION OF THREE PASSIVE-INTEGRATING CHARCOAL DETECTORS FOR MEASURING RADON CONCENTRATIONS

THESIS

David L. Sharp
Captain, USAF
AFIT/GNE/ENP/90M-6

AFIT/GNE/ENP/90M-6

EVALUATION OF THREE PASSIVE-INTEGRATING CHARCOAL DETECTORS FOR MEASURING RADON CONCENTRATIONS

THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Nuclear Engineering

David L. Sharp, B.S.

Captain, USAF

March 1990

Preface

The purpose of this study was to calibrate and study the response of three types of time-averaging, passive radon detectors. This study is important because of the increasing problem of radon level buildup in structures. Radon levels are rising because of efforts to make buildings more air-tight to conserve energy. As a structure becomes more air-tight, the air exchange rates decrease; resulting in a buildup of radon concentrations. This study will help determine the accuracy of one of the more common radon measurement techniques - charcoal adsorption.

I would like to acknowledge the great deal of assistance I received from my advisor, Dr. George John. His guidance and constant pressure to work at a steady pace helped me obtain the data I needed to get meaningful results. I am also indebted to Dr. Andreas George of the DOE's Environmental Measurements Laboratory in New York City. He provided his time and effort to allow our use of their calibrated chamber at short notice when the Mound facility went down. My gratitude is also extended to the base employees that allowed me to distribute detectors in their work places.

David L. Sharp

Table of Contents

List of Figures

List of Tables

Abstract

Three types of passive-integrating charcoal detectors that determine Radon-222 (Radon) concentrations in air samples were studied. Each detector type examined uses activated charcoal to adsorb radon from air samples that enter through a diffusion barrier. This results in a time-integrated sample. The three detector types analyzed were liquid-scintillation (LS) vials, and canisters with and without moisture-adsorbing desiccant. The LS vials contain a mixture of charcoal and desiccant.

All three types of radon detectors were exposed in a radon chamber where the concentration of radon was known, to allow calibration of the detectors. The results from the exposure to a known radon concentration were used to determine the sensitivity of each detector type.

Since the LS vials had not previously been used for studies at AFIT, the optimum procedure for exposing, processing, and counting the vials was established. An automated liquid-scintillation counter (LSC) was used for determining the radon levels detected by the LS vials. The variability in the radon concentrations computed by the LSC for repeated counting of a single vial was examined. The variability across vials was found to be between 1 and 4 percent. Reproducibility of radon adsorption by a group of vials exposed simultaneously was also examined. Values for the reproducibility experiment across a set of ten vials counted for 4 cycles had a standard error of 1.4 percent.

Experiments were performed to determine the saturation point of the detectors exposed to a high radon concentration (> 100 pCi/l). The vials appeared to saturate near the 24 hour point, while canisters with desiccant did not seem to saturate. A blind test was performed where the detectors were exposed to a known concentration, prepared, counted, and then the concentrations measured were compared to actual values. The measured values were within < 1% to about 8% of the actual concentrations. Exposure times of 24 to 48 hours were recommended for the vials, and 3 to 7 days for the canisters.

EVALUATION OF THREE PASSIVE-INTEGRATING CHARCOAL DETECTORS FOR MEASURING RADON CONCENTRATIONS

I. Introduction

Purpose

The purpose of this thesis is to calibrate and study the response of three types of passive rau detectors. These detectors can then be used to determine environmental levels of radon.

Background

Previous studies of environmental radon have been conducted at AFIT. In 1984, D. R. Little examined the effect of using an electrostatic precipitator to reduce indoor radon levels. He measured progeny activity by using the modified-Tsivoglou method. Charles Gill (8:45) built time-averaging charcoal adsorption detectors in 1985 designed after Cohen's work at the University of Pittsburgh (3:457-463). In the fall of 1985 J. Weidner (15:1) examined the effectiveness of three types of air treatment methods in a residence. Weidner also used the modified-Tsivoglou method to measure radon progeny concentrations. In 1987, J. Bouchard (2:1) measured radon levels in residences and radium levels in local geology to allow comparison. The charcoal canisters built by Gill were used to measure indoor radon levels, and a Lucas cell was used to determine the radium content of soil. He also set-up a radon chamber for laboratory exposures.

Radon is a colorless, odorless, inert gas. When naturally-occurring long-lived radionuclides, such as ^{238}U, ^{235}U, and ^{232}Th, decay; radon is one of the resulting products. In the series beginning with ^{238}U, ^{226}Ra which has a half-life of 1600 years, is produced (14:45). This is the parent radionuclide of ^{222}Rn, which has a 3.82 day half-life and is the major contribution of radon radioisotopes in the atmosphere (14:45). The thorium series produces ^{220}Rn, also known as thoron. The generation rate of thoron is similar to that for radon; however, the much shorter half-life of thoron (56 seconds) precludes its emanation from the soil (14:44). Therefore, thoron is not considered part of the radon hazard. Radon-219 is a member of the actinium series, but it is not considered a hazard because the parent isotope of this series, ^{235}U, accounts for only 0.71% of naturally-occurring uranium. In addition, ^{219}Rn has only a 3.96 second half-life, so most of the ^{219}Rn will decay before it can escape from the ground (14:44). Therefore, ^{222}Rn is the radioisotope of concern.

Radon-222 (radon) decays successively into the elements polonium, lead, and bismuth which are all alpha or beta emitters. Table 1 shows the primary decay chain for radon (excluding paths with less than 0.1% of the decays). The decay chain ends with lead-210 for our purpose because of its relatively long half-life, 22.3 years (14:43). The four radionuclides in the chain between Rn-222 and Pb-210 are referred to as the radon daughters or progeny.

The parent of the decay chain resulting in ^{222}Rn, ^{238}U, is present in rock and soil and is relatively stable with a half-life of 4.5×10^9 years (14:47). Uranium-238 is found in widely-varying concentrations in different locations of the earth, depending greatly upon the type of material present. Since the radon radioisotope of interest, ^{222}Rn, is a decay product of ^{238}U, these concentrations are a concern. The concentration of ^{238}U is especially high for bituminous shale and phosphate rock (5:130).

Radon is an inert gas with a half-life of several days, so it can diffuse through soil and escape to the atmosphere. Radon emanation from soil is affected not only by the concentration of ^{238}U in the region but is also dependent upon several physical and meteorological factors. The physical factors include the condition, porosity, and moisture content of the soil, as well as the depth at which the radon is formed. A more porous soil would allow a higher radon emanation rate; however, soil covered in ice or snow would reduce the diffusion rate. Usually, only that radon which originates in the soil near the surface will reach the atmosphere. The National Council on Radiation Protection and Measurement (NCRP) uses as a rough guide that about 10% of the radon formed in the top meter of soil will escape (1:7).

The meteorological factors which affect radon emanation rates include barometric changes, temperature differentials, and wind velocities. For example, the lower the barometric pressure, the easier radon gas can diffuse out of the soil; thus increasing radon concentrations. Higher barometric pressure would result in lower radon emanation rates (5:143,11:4).

Table 1: Principal Decay Properties of Radon And Its Progeny

		Main Radiation Energies And Percents					
Nuclide	Half-life	Alpha		Beta		Gamma	
		MeV	%	MeV	%	Mev	%
Rn-222	3.824 d	5.49	100	-	-	-	-
Po-218	3.05 min	6.00	100	-	-	-	-
Pb-214	26.8 min	-	-	0.67 0.73	48 42	0.30 0.35	19 37
Bi-214	19.7 min	-	-	<1.5 1.5-2.5 3.27	32 49 18	0.61 1.12 1.76	46 15 16
Po-214	163.7 μs	7.69	100	-	-	-	-

Radon gas diffusing out of the soil affects both outdoor and indoor air. Radon concentrations in soil gas have been found to range from 7000 Bequerel/m³ (189 pCi/l) to more than 200,000 Bq/m³ (5400 pCi/l) with typical values between 20,000 and 40,000 Bq/m^3 (540-1080 pCi/l) (9:14). Data from several countries indicate average radon concentrations in outdoor air to be 0.1 to 0.3 pCi/l. The concentration at a given location varies with time, with the highest levels in the early morning hours and the lowest levels in the late afternoon (6:5). Generally, indoor radon levels are considerably greater than those outdoors. Radon enters structures mainly from soil gas seeping through gaps in the building foundation (cracks, drains, and pipe penetrations). However, soil gas emanation is not the only source of indoor radon.

Other sources of indoor radon include the building materials of the structure, the water supply, and, if applicable, natural gas. Building materials that are derived from the earth, such as stone and sand, contain uranium and radium and; therefore, generate radon. If the material is porous, like brick and concrete, the radon is able to escape into the air.

Radon and radium are both soluble in water. Ground water picks up radium and radon from the surrounding rock and soil. If the water picks up radon, the radon itself and its progeny will decay away in a few days. Therefore, only the most recent path of the water is important. On the other hand, if the water contains a significant portion of radium (1600 year half-life); then the complete history of the water movement is important. The typical radon level for United States water supplies is around 1000 pCi/l or less (1:53). The concern is not with drinking the radon-bearing water, but the release of the radon into the air. Radon can be released from water in various ways. When the water is heated, radon can escape more readily because the solubility of radon in water decreases as the temperature increases. Radon is also released when water is aerated, such as in a faucet or shower head. Recent studies have found an average value of about 0.1 pCi/l of radon in the air per 1000 pCi/l in the water supply (1:53-54).

Another source of indoor radon is natural gas. Since natural gas is derived from underground reservoirs it contains radon. When natural gas is burned in domestic appliances or furnaces, radon is released into the air. Assuming gas furnaces and water heaters are vented outside the house, unvented stoves are the main source of radon in the house from natural gas. However, even if the radon concentration in the natural gas is assumed to be abnormally high, the resulting average radon concentration inside the house will be only 0.1 to 0.2 pCi/l (1:55).

Radon Hazard

Although we are concerned with indoor radon levels, it is not the radon itself which creates the hazard. The health risk arises from the inhalation of the short-lived radon progeny, since the inert radon is almost totally exhaled. Three possible states exist for the progeny: unattached, attached to aerosols, and deposited on surfaces. Only the airborne fraction is of importance from a radiological perspective. The level of the airborne fraction, as well as the distribution between attached and unattached fractions, is highly dependent on the condition of the environment. Progeny attach to airborne particles and droplets in the air. The fraction attached to aerosols is not the major health concern because most of these particles are stopped by mucus and cilia before they can reach the lung.

The unattached fraction is the main concern. When unattached progeny are inhaled, they tend to deposit (plateout) in the upper respiratory tract, especially in the bronchi. This area is considered to be the most likely region for tumors to develop (12:36,15:5). The term "working level" is used to describe the radon progeny concentrations in a way that reflects their biological hazard.. The concept of working level is described in Appendix A.

Radon Measurements

Radon levels in air can be determined in a variety of ways. Some methods use a "grab sample" to find the radon level at a particular instant. Lucas scintillation cells use this grab-sample technique to take instantaneous measurements. Other detectors take integrated measurements over a certain period of time. For example, alpha track-etch detectors take integrated measurements over long periods of time (months); whereas, integrating charcoal adsorption detectors take integrated measurements over a period of a few days. All of these methods directly measure the radon concentration in the air sampled. Methods such as the modified-Tsivoglou and the Kusnetz method; however, determine the level of radon progeny in the air sample (6:25-29).

Scope of Thesis

For this study, three types of integrating charcoal adsorption radon detectors were examined. Two of the radon detectors are charcoal canister devices, one with moisture-adsorbing desiccant and the other without desiccant. The other detector is a liquid scintillation vial (distributed by Packard Instrument Company and called Pico-Rad) which contains a mixture of charcoal and desiccant. The techniques were developed which will allow the processing and counting of the Pico-Rad charcoal vials, and studies were performed to assess the reproducibility and variability of the count rates for the vials counted with a liquid-scintillation counter (LSC). The three types of radon detectors were calibrated to allow their use in measuring radon levels in air samples. All three types of detectors were exposed to a known radon concentration, processed, and counted to determine the radon concentrations. The concentrations determined from counting were then compared to the known concentrations. Various aspects of the three detector types were analyzed, such as saturation points and sensitivity. Finally, LS vials and canisters without desiccant were used to measure radon levels in selected buildings on Wright-Patterson Air Force Base (WPAFB).

Sequence of the Report

Chapter II contains descriptions of the test equipment used. Chapter III explains the experimental methods used. Chapter IV contains a review of the data obtained during testing and the results. Chapter V contains the conclusions drawn from the test results and includes recommendations for improvements and further study.

II. Description of Test Equipment

Radon Detectors

Three types of radon detectors were used in this study. The first type is a charcoal canister developed by Cohen (4:457-463) and built by Gill (8:45). This detector is a 1 inch by 3 inch diameter ointment can containing 27 grams of charcoal (1.5 cm in depth). The charcoal is separated from the ambient air by a silk screen diffusion barrier covering a 3/4-inch diameter opening in the lid of the can. When the detector is not in use, the 3/4-inch opening is covered by a piece of aluminum foil adhered to duct tape.

The second type of detector is the same charcoal canister described above with a bag of desiccant (silica gel) covering the 3/4-inch opening inside the silk screen. The desiccant bag is held as tightly as possible to the screen by taping the bag's ends to the inside of the can lid with duct tape. The desiccant bag completely covers the opening, but it was not able to be held tightly against the diffusion barrier. Desiccant is added to the detector to absorb moisture because water contends with radon for adsorption sites on the charcoal. Therefore, moisture can reduce the capacity of the detector to adsorb radon.

A polyethylene vial containing approximately 1.3 grams of charcoal and about 0.9 grams of desiccant is the third type of radon detector which was used. In this case, the charcoal and desiccant are mixed together inside a plastic container which is attached to the inside of the vial. This container is approximately 6 centimeters (cm) deep by 2 cm in diameter, and is separated from the ambient air by a diffusion barrier built into the vial. Figure 2 is a sketch of the vial. The vial has a screw-on cap which is removed for exposure.

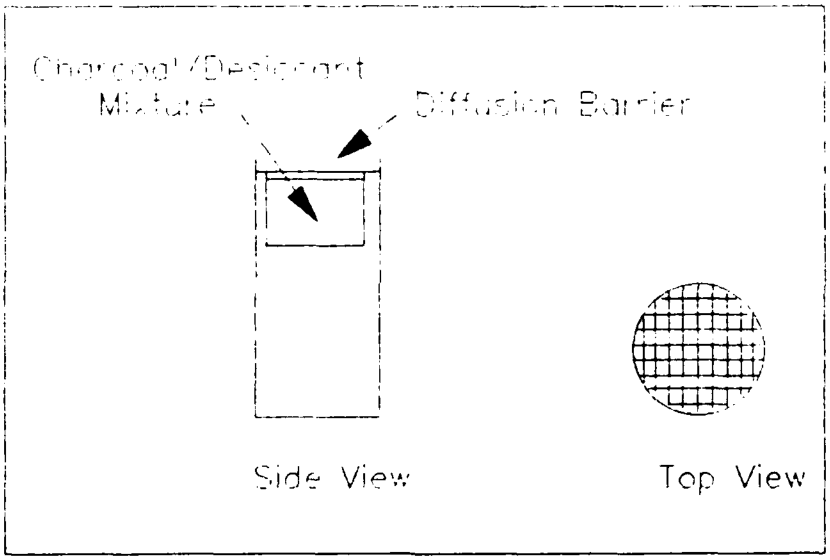

Figure 1. Cross-Section of a Pico-Rad Liquid-Scintillation Vial

Radon Chamber

The radon chamber used for this study was set up by Bouchard in 1987 for his study of the relationship between radon levels in homes and the local geology and fill material. This chamber is a closed system consisting of a 250 liter glovebox containing a radon source, a small fan, and an aquarium pump as shown in Figure 2. The radon source used was a beaker containing 0.1 μCi of Radium-226. The aquarium pump was used to flow air from the chamber out through a continuous monitor and then back into the chamber. The fan forced air flow over the radon source into the left-rear corner of the glovebox (as seen from the top of the chamber).

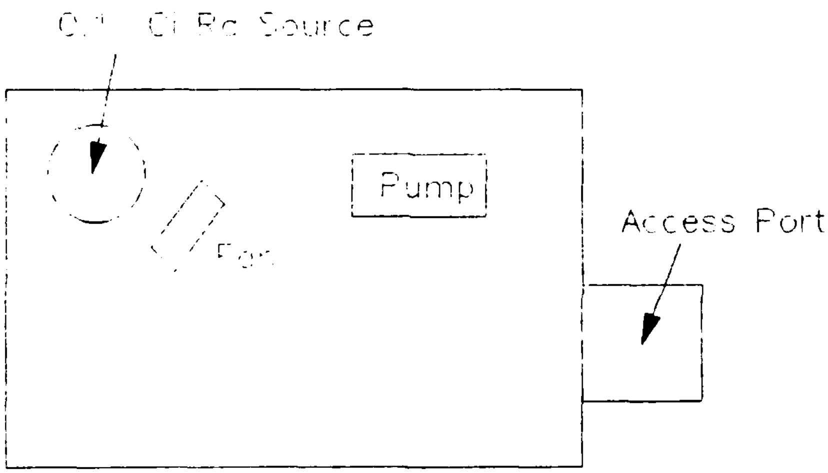

Figure 2. AFIT Radon Chamber Layout (Top View)

The humidity inside the chamber was measured periodically for the last 30 days of the study. A Nuclear Data (ND) 680 multichannel analyzer (MCA) was used in the multiscale mode to measure the counts from the continuous monitor, which was a Lucas cell. A 400 second counting interval was used for each channel of the MCA.

Liquid-Scintillation Counter

An automated liquid-scintillation counter (LSC) was used to count one of the integrating-passive radon detectors examined in this study, a vial containing charcoal and moisture-absorbing desiccant. The LSC consists of three major elements. an automated sample changer, a counting chamber, and a computer for directing sample manipulation and for processing data.

The LSC counts the alpha and beta particles from all five decays in the radon decay chain. These emitted particles interact with the liquid-scintillation cocktail in the vial. Liquid-scintillation cocktail consists of two main ingredients; a solvent and a solute. The solute is a fluor. Emitted alpha or beta particles collide with and excite solvent molecules in the scintillation cocktail. Excited solvent molecules can transfer their energy to other solvent molecules or to solute molecules. When a solvent molecule transfers its energy to a solute molecule, the orbital electrons of the solute molecule reach an excited state. As these excited electrons return to their ground states, they release photons. One particle emitted by the radon or one of its progeny will excite many solute (fluor) molecules. To a first approximation this is a linear conversion of particle energy to photons, so the intensity of the light emitted by the fluor is proportional to the initial energy of the alpha or beta particle.

The photons emitted from the solute can strike the photomultiplier tube (PMT) located adjacent to the counting chamber where they are converted to an electrical signal (a reflector is used to increase the number of photons striking the PMT). The conversion is linear, so the signal strength is directly proportional to the number of photons detected by the photocathode of the PMT. Our system contains two PMTs located on opposite sides of the counting chamber. Nuclear decay events produce around ten photons per keV of energy, and this energy is dissipated in an amount of time on the order of 5 nanoseconds (13:3-9). Since the emitted particle produces many photons, both PMTs will be stimulated simultaneously. The signal from each PMT goes to a coincidence circuit with a resolving time of 20 nanoseconds. A threshold particle energy exists below which both PMTs will not be stimulated within the required resolving time. For our system this coincidence threshold occurs below 1 keV (13:9).

III. Experimental Method

Radon Concentration Determinations

For the two types of charcoal canister detectors, a thallium-activated, sodium iodide [NaI(Tl)] scintillator and a multichannel analyzer were used to obtain a pulse-height spectrum of the gammas emitted in the decays of Pb-214 and Bi-214. The gross counts from 220-390 keV (Pb-214) and those from 550-680 keV (Bi-214) were measured using thirty-minute counting times.

The results of the gross gamma counts in the energy regions of interest were entered into the computer programs for canisters with and without desiccant - "RADONDESX" and "RADONX," where X is the length of exposure in days. The initial program was developed by Charles Gill (8:40) and fine-tuned by Dr G. John. A listing of the program appears in Appendix C. The time since the canisters were sealed and the background gamma counts in the two regions of interest were used as input to the program. The program then calculates the net gamma counts, corrects the counts for radioactive decay of radon, and calculates the radon concentration in picocuries per liter (pCi/l).

The third type of detector, the polyethylene vials, are counted with the automated liquid-scintillation counting system described above. The LSC was used to obtain a pulse height spectrum of the alphas and betas emitted by all five members of the radon decay chain. The gross counts from 20-900 keV are measured, this value is divided by the count time, and a gross count rate is determined by the system.

The vials were prepared for counting by adding 14.0 milliliters (ml) of Insta-Fluor liquid-scintillation cocktail as soon as possible after exposure. Counting was started after radiological and chemical equilibrium had been achieved between the radon and the cocktail. The vials were placed inside the LSC in the sample changer, and counting was initiated when the vial was transferred from the sample changer into the counting chamber. Ten minute counting times were used for the majority of this study.

Detector Calibration

All three types of radon detectors were exposed in a chamber of known radon concentration at the Department Of Energy's Environmental Measurements Laboratory (EML) in New York. Ten detectors of each type were exposed in pairs to known radon concentrations for five different lengths of exposure. The vials were exposed for periods of time from 15.5 hours to 72 hours, and the canisters were exposed for periods of 24 to 168 hours (1 to 7 days). Upon their return, the detectors were counted by the appropriate counting system, and the results were used to determine conversion factors for all three detector types. The conversion factors convert count rates to concentrations of radon in pCi/l. The humidity in the chamber was not controllable during the exposures, but the values of both humidity and temperature were recorded for the entire exposure time.

Liquid-Scintillation Vial Studies

Establishment of Standard Protocol. Since the liquid-scintillation (LS) vial method of measuring radon levels in air samples had not been previously used at AFIT, an optimum procedure for exposing, processing, and counting the vials had to be established. This was done by exposing sets of vials in our radon chamber (described above) for certain periods of time, and determining the amount of time required for the radon cocktail mixture to reach chemical and radiological equilibrium. The time after cocktail addition must be determined when the most accurate representation of the actual radon concentration is found. When these questions are answered, a standard method (protocol) for processing the LS vials can be established.

Variability Studies. The variability of the results from the LSC for the LS vials was examined. LS vials were exposed in the radon chamber, processed, and counted repeatedly with the LSC. All of the results for these repeated counts were compiled, and the counting statistics for the LSC were calculated. The counts from the Lucas cell continuous monitor were used to normalize the radon concentrations in the chamber for each exposure.

Reproducibility of Vial Response. A study of the reproducibility in individual LS vial response to a given radon concentration was performed. A group of vials were exposed together in the AFIT radon chamber, processed in the same manner, and counted with the LSC. The statistical variability in the resulting count rates/radon concentrations was evaluated.

Detector Saturation

LS vials and canisters with desiccant were exposed in the AFIT radon chamber for varying lengths of time to determine if a saturation point was reached. Vials were exposed for periods between 2 and 72 hours, while canisters with desiccant were exposed for periods of 1 to 7 days.

Detector Sensitivity

The sensitivity for each type of radon detector was examined. The sensitivity of a radon detector is a measure of the ability of a device to differentiate low radon levels (< 1 pCi/l). Sensitivity values were determined for each detector type and for each exposure time for which data were available. The results from the EML chamber exposures were used to calculate the sensitivities.

Comparison of Calculated Rn Concentrations and Known Exposure Values

A pair of each type of radon detector was exposed in EML's calibrated chamber. The vials were sent back to our laboratory without the radon concentrations to which they were exposed (these were obtained later). The detectors were processed, and the results were then compared with the exposed concentrations.

Environmental Measurements

Environmental radon levels were measured in various buildings on WPAFB. For this study, a canister without desiccant was exposed next to a liquid-scintillation vial to allow comparison. Where applicable, detectors were placed on different floors of the building to also allow comparison across locations within a structure.

IV. Results

Detector Calibration

Conversion factors were obtained for the charcoal canisters with and without desiccant and for the liquid-scintillation vials. The detectors exposed in the EML radon chamber were counted with the appropriate scintillator, and the results from the counts were averaged for a particular detector and a particular exposure time. The averaged counts or count rates were divided into the actual radon concentrations provided by EML to yield a conversion factor. Units for these conversion factors are pCi/l per cpm for the vials and pCi/l per net corrected counts in 30 minutes (30 minutes is the count time for canisters). Tables 2 and 3 list the conversion factors (FAC) calculated for the charcoal canisters with and without desiccant for each exposure time. Table 4 lists the conversion factors (FAC) calculated for the liquid-scintillation vials for each exposure time. The errors in the count rates are random errors from counting statistics. Values of FAC Contain a 5% systematic error for the EML radon concentrations. The results of both type of error (in percentages) were added and the result multiplied by the value of FAC. All errors listed in Tables 2 through 5 and in the rest of the document are one standard deviation.

A comparison of the average net corrected counts per 30 minutes for canisters with and without desiccant shows a significant difference in the amount of radon adsorbed by the two types of canisters. The canisters with desiccant bags had a lower value for average net corrected counts per 30 minutes than did the canisters without desiccant exposed simultaneously in the EML chamber. This difference ranged between 19 percent and 36 percent lower average net corrected count rates for canisters with desiccant compared to these without desiccant.

Table 2. Conversion Factor (FAC) Data For Canisters Without Desiccant

Exposure Time (Hours)	EML Radon Concentration (pCi/l)	Average Net Corrected Counts/30 Mins	FAC (10^{-3} pCi/l per Net Corrected counts/30 Mins)
24	48.0	11567 ± 231	4.15 ± .29
48	47.8	19500 ± 70	2.45 ± 0.13
72	49.3	23025 ± 165	2.14 ± 0.12
120	44.6	24678 ± 1036	1.81 ± 0.17
168	46.2	27345 ± 438	1.69 ± 0.11

Table 3. Conversion Factor (FAC) Data For Canisters With Desiccant

Exposure Time (Hours)	EML Radon Concentration (pCi/l)	Average Net Corrected Counts/30 Mins	FAC (10^{-3} pCi/l per Net Corrected counts/30 Mins)
24	48.0	7434 ± 195	6.46 ± 0.17
48	47.8	13091 ± 76	3.65 ± 0.20
72	49.3	16789 ± 105	2.94 ± 0.17
120	44.6	20059 ± 209	2.22 ± 0.13
168	46.2	20390 ± 951	2.27 ± 0.22

Table 4. Conversion Factor (FAC) Data For Liquid-Scintillation Vials

Exposure Time (Hours)	EML Radon Concentration (pCi/l)	Average Net Corrected Counts/Min	FAC (10^{-3} pCi/l per Net Corrected Counts/Min)
15.5	49.3	1381 ± 3.5	35.7 ± 1.9
24	48.0	1573 ± 15	30.5 ± 1.8
30.5	48.0	1715 ± 121	28.0 ± 3.4
48	47.8	1835 ± 34	26.1 ± 1.8
72	49.3	1809 ± 168	27.3 ± 3.9

The conversion factors decrease with increasing length of exposure for the canisters without desiccant. This was also true for the values of FAC found for the vials and the canisters with desiccant up to the value for the longest exposure times. The values of FAC for the canisters at 120 and 168 hours were not statistically different from each other. The FAC values for the LS vials at 24 through 72 hours were not statistically different. These values were used to determine detector sensitivity (examined later).

Liquid-Scintillation Vials

Standard Protocol. Various experiments were run to determine a preferred method (protocol) for preparing and counting the exposed liquid-scintillation vials. The optimum process and length of time required for the radon/cocktail mixture to reach radiological and chemical equilibrium had to be established. Also, a determination of the optimum time after cocktail addition to count the vials with the LSC had to be made.

The time required for the radon/cocktail mixture to reach equilibrium was determined experimentally by counting two vials (#5 and #6 exposed together in the radon chamber) immediately after cocktail addition. Counting was continued until the count rates levelled off. Figure 3 shows the count rate (at t = 0) corrected for decay versus time after cocktail addition for both vials. The count rates are corrected for radiological decay, but are not normalized to the Lucas cell counts during the exposure. Results for this experiment show that a time of approximately 24 hours after cocktail addition is required for equilibrium to be reached. A decision was made to invert the vials for the first 24 hours after cocktail addition to allow the best interaction between the charcoal and the cocktail.

Three procedures were tested to find the optimum process for handling the LS vials once equilibrium had been reached. For one procedure, the vials were inverted immediately after cocktail addition and were turned upright and placed in the LSC at the 24 hour point after cocktail addition. Counting was initiated after the vials were inside the LSC for a minimum of 2 hours. The reason for the two hour wait after placing the vials in the LSC before counting is to allow the vials to reach thermal equilibrium with the LSC (about 14 °C). This complete process (referred to as standard protocol 1) was used for seven sets of vials with three vials in each set. The results for a representation of these runs are included in Figures 3 - 6. Errors for these count rates are between 15 and 21 counts per minute (cpm) which is around 0.5 percent.

For the second procedure (standard protocol 2), the vials remained inverted for 48 hours after cocktail addition, were turned upright and placed in the LSC, and counting was started after at least two hours had passed. This protocol was tried because the count rates seemed to be converging past the 48 hour point after cocktail addition. Protocol 2 was used for one set of three vials. Figure 7 contains the results.

For the third procedure (standard protocol 3), the vials again remained inverted for the first 24 hours after cocktail addition. At the 24 hour point, the vials were turned upright but left standing outside the LSC for an additional 24 hours. The vials were then placed in the LSC and counting was started after the vials were inside the LSC for at least two hours. This protocol was established because charcoal sediment was found settling out on the bottom of the vials after a few days. By turning the vials upright for a total of 26 hours before counting, any charcoal particulates could settle out of the cocktail. Protocol 3 was used for four sets of vials with three vials in each set. Figures 8 - 11 contain the results for these four runs. The errors are similar to the previous values noted (about ± 20 cpm).

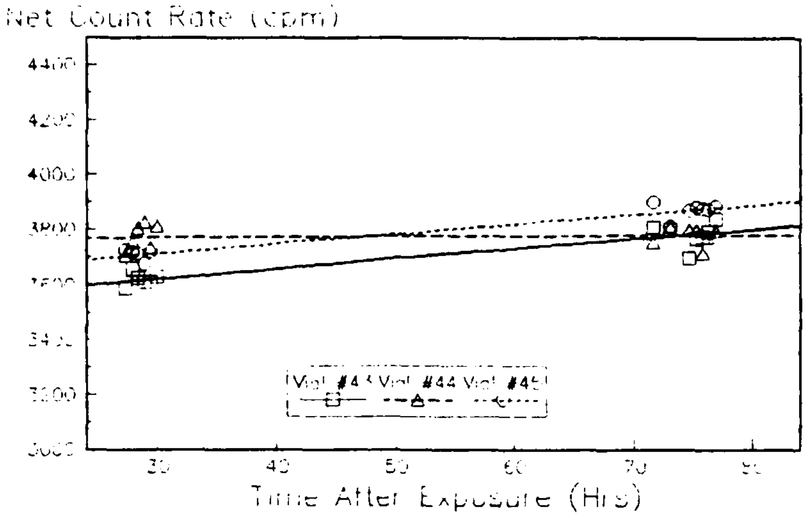

Figure 3. Count Rate Versus Time for Vials Prepared Per Standard Protocol 1 (Replicate 1). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

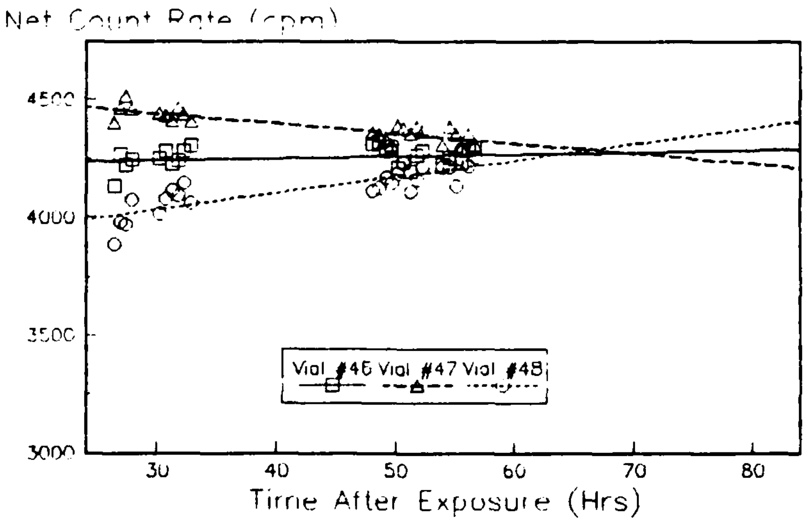

Figure 4. Count Rate Versus Time for Vials Prepared Per Standard Protocol 1 (Replicate 2). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

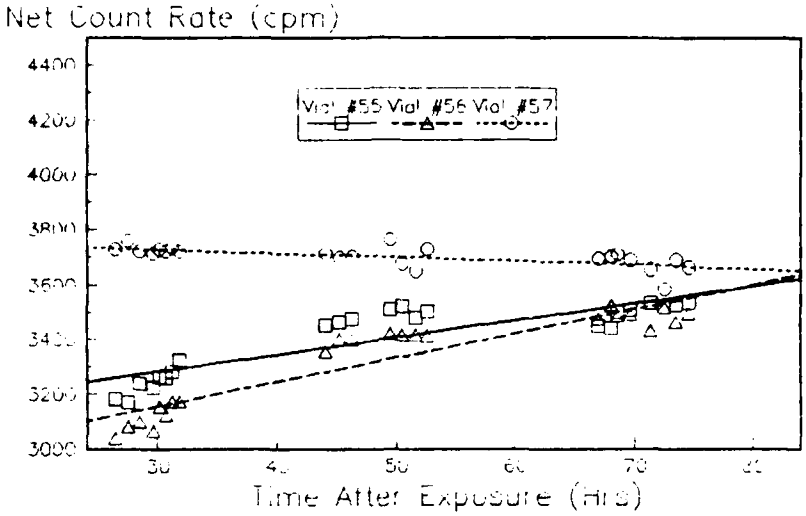

Figure 5. Count Rate Versus Time for Vials Prepared Per Standard Protocol 1 (Replicate 3). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

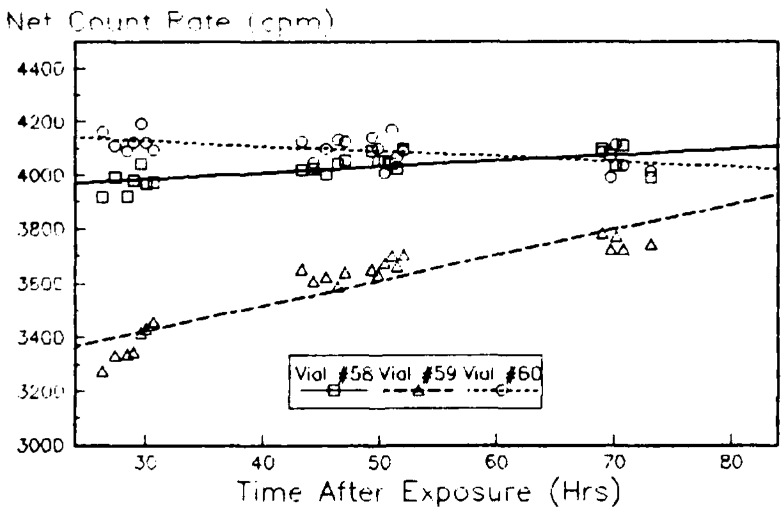

Figure 6. Count Rate Versus Time for Vials Prepared Per Standard Protocol 1 (Replicate 4). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

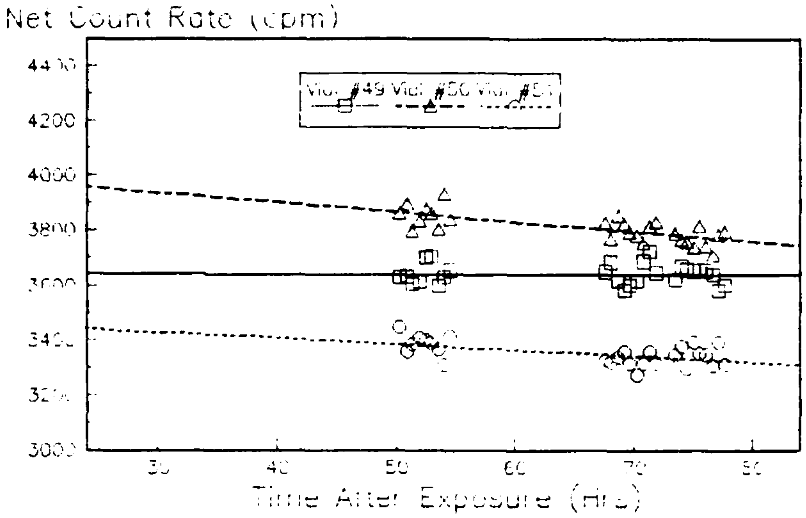

Figure 7. Count Rate Versus Time for Vials Prepared Per Standard Protocol 2 (Replicate 1). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

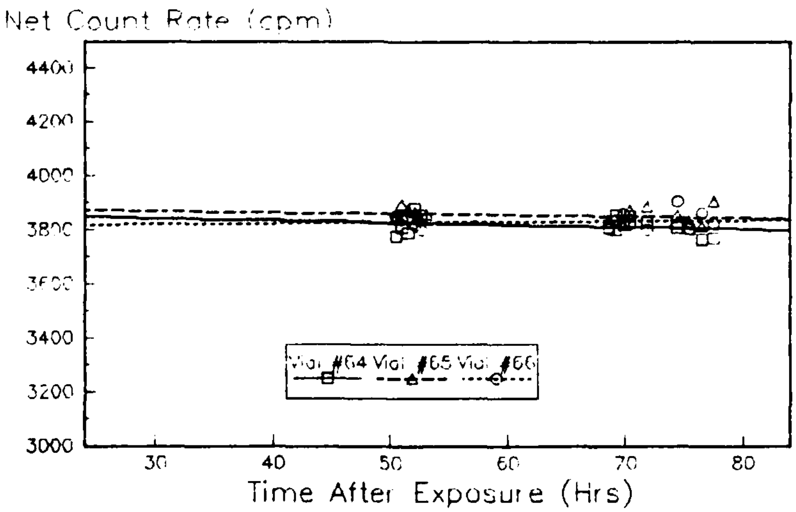

Figure 8. Count Rate Versus Time for Vials Prepared Per Standard Protocol 3 (Replicate 1). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

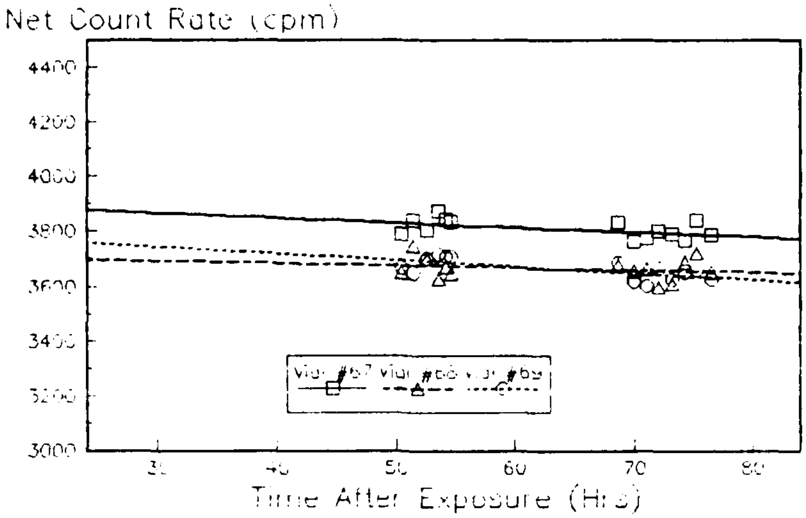

Figure 9. Count Rate Versus Time for Vials Prepared Per Standard Protocol 3 (Replicate 2). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

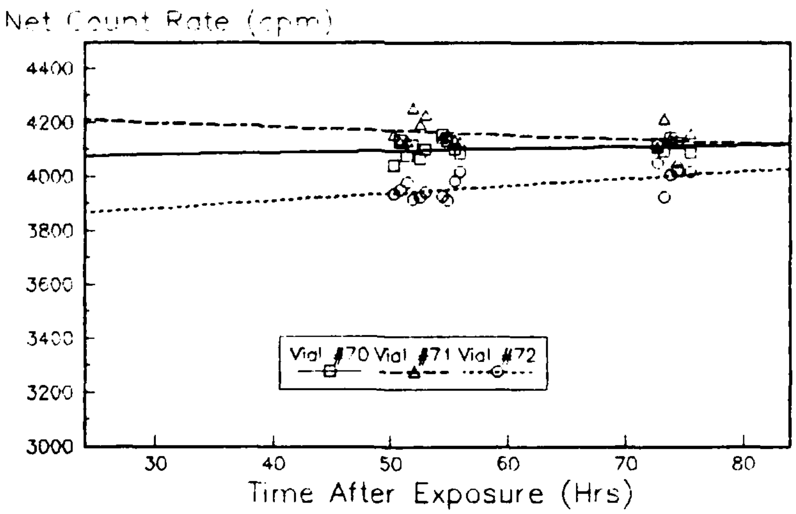

Figure 10. Count Rate Versus Time for Vials Prepared Per Standard Protocol 3 (Replicate 3). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

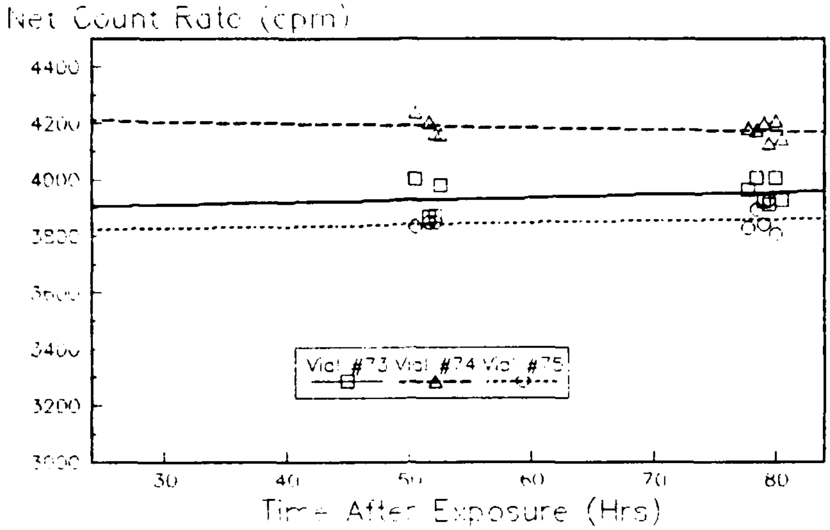

Figure 11. Count Rate Versus Time for Vials Prepared Per Standard Protocol 3 (Replicate 4). The Count Rates Are Corrected to t_0, the Time of Closure, and They Are Normalized to Lucas Cell Counts.

The plots for each protocol were examined for trends. Plots for the vials prepared per standard protocol 1 show converging count rates with increasing time after exposure for six of the seven runs. The exception, vials #52 - #54, had count rates that were tightly grouped for the first set of counts (26 to 30 hours after exposure) and then diverged with increasing time. Standard protocols 2 and 3 were established to determine if the count rates would be tightly grouped for the first set of counts. The plot for standard protocol 2 shows converging count rates for two of the vials by 72 hours after exposure, but the count rates for the three vials differ by approximately 500 cpm for the first set of counts. The goal is to have the most accurate value of the count rate for the first count. The four plots for standard protocol 3 show almost no change in the count rates with increasing time. The trends are nearly flat lines, which is part of the desired result. This protocol appears to be the best for getting count rates from the first few counts which are representative of a wide period of time after cocktail addition.

Variability. The variability of the count rates/radon concentrations measured by the LSC was checked for 36 vials exposed in the radon chamber. Tables 5 through 7 include the average net corrected count rates in cpm, the average radon concentrations in pCi/l, and the percent error in the average radon concentration for these 36 vials. Table 5 includes the data for the 15 vials processed per standard protocol 1. Table 6 includes the data for the three vials processed per standard protocol 2. Table 7 includes the data for the nine vials processed per standard protocol 3. The average net corrected count rate values are corrected for decay (by the LSC) and normalized to the Lucas cell counts during the exposure. Radon concentrations were calculated using the conversion factor, FAC, computed for the EML 24 hour exposure vials.

The errors caused by statistics of counting for the average radon concentrations calculated for each vial ranged from .20% to 1.2%. Both of these extreme values occurred for vials prepared per standard protocol 1. The errors caused by statistics of counting for the vials prepared per standard protocols 2 and 3 were similar, ranging from 0.21 to 0.32%.

Table 5. Vial Count Rate And Radon Concentration Variability For Repeated Counts Of A Single Vial (Standard Protocol 1 Vials)

Vial Number	Number Of Cycles	Average Net Corrected Count Rate (cpm)	Average Radon Concentration C_i (pCi/l)
46	25	4255 ± 8	129.87 ± 0.26
47	25	4386 ± 12	133.88 ± 0.36
48	25	4126 ± 20	125.94 ± 0.60
52	27	3580 ± 12	109.28 ± 0.37
53	27	3889 ± 13	118.71 ± 0.40
54	27	3544 ± 9	108.17 ± 0.27
55	23	3406 ± 27	103.96 ± 0.83
56	23	3330 ± 36	101.7 ± 1.11
57	23	3700 ± 8	112.9 ± 0.25
58	23	4026 ± 11	122.89 ± 0.34
59	23	3586 ± 34	109.5 ± 1.0
60	23	4098 ± 11	125.07 ± 0.34
61	22	3370 ± 41	102.9 ± 1.3
62	22	3807 ± 34	116.2 ± 1.0
63	22	4028 ± 20	122.96 ± 0.61

The statistical results for all of the vials in Table 5 are as follows:

$\bar{C} = 116$

$s_{n-1} = 10$

$s_{\bar{C}} = 2.7$

Where,

$\bar{C}$ is the mean of the average radon concentrations

s_{n-1} is one standard deviation

$s_{\bar{C}}$ is the standard error of the mean

Note: The count rates in Tables 5 through 7 are corrected for decay and normalized to Lucas cell counts.

Table 6. Vial Count Rate And Radon Concentration Variability For Repeated Counts Of A Single Vial (Standard Protocol 2 Vials)

Vial Number	Number Of Cycles	Average Net Corrected Count Rate (cpm)	Average Radon Concentration C_1 (pCi/l)
49	27	3641 ± 7	111.14 ± 0.22
50	27	3809 ± 10	116.27 ± 0.30
51	27	3353 ± 8.2	102.35 ± 0.25

The statistical results for all of the vials in Table 6 are as follows:

$\bar{C} = 110$

$s_{n-1} = 7.0$

$s_{\bar{C}} = 4.1$

Table 7. Vial Count Rate And Radon Concentration Variability For Repeated Counts Of A Single Vial (Standard Protocol 3 Vials)

Vial Number	Number Of Cycles	Average Net Corrected Count Rate (cpm)	Average Radon Concentration C_i (pCi/l)
64	15	3816 ± 9	116.48 ± 0.28
65	15	3852 ± 8	117.58 ± 0.25
66	14	3832 ± 8	116.97 ± 0.25
67	14	3809 ± 10	116.25 ± 0.29
68	14	3665 ± 11	111.88 ± 0.33
69	14	3663 ± 10	111.79 ± 0.31
70	15	4106 ± 8	123.33 ± 0.26
71	15	4156 ± 13	126.85 ± 0.41
72	15	3967 ± 12	121.10 ± 0.37

The statistical results for all of the vials in Table 7 are as follows:

$\bar{C} = 118$

$s_{n-1} = 5.0$

$s_{\bar{C}} = 1.7$

errors for the vials prepared per standard protocol 1 were generally higher. These vials were counted over wider periods of time than the others (from 26 to 80 hours after exposure as opposed to 50 to 80 hours after exposure), but they had more counts, reducing the error of the mean value. The standard errors across a given protocol range between 1.4% for protocol 3 to 3.7% for protocol 2. Protocol 1 had a standard error of 2.3%.

Reproducibility. A study of the reproducibility of the results from the LS vials was performed. The count rates obtained from the LSC for a set of vials exposed together in the AFIT radon chamber were compared. Ten LS vials (#5-#14) were exposed in the chamber for 72 hours. LS cocktail was added to the vials, and they were allowed to stand upright at room temperature (Note: two vials were placed in the LSC immediately after cocktail addition for a separate study). The remaining vials were placed in the LSC 22 hours after cocktail addition and counting of all ten vials was started 22.5 hours after cocktail addition. The set of vials was cycled four times in the LSC. Each cycle included one 30 minute count per vial. Table 8 lists the average normalized count rates with the equivalent concentrations along with the corresponding errors for these ten vials. The radon concentrations listed were computed using the conversion factor, FAC, calculated for the EML 72 hour exposure vials since a three-day exposure period was used.

Table 8. Reproducibility Values For Each Cycle Of Counts Of Ten LS Vials Exposed Together In The AFIT Radon Chamber

Cycle Number	Average Normalized Count Rate (cpm)	Average Radon Concentration C_i (pCi/l)
1	3523 ± 111	96.0 ± 9.5
2	3584 ± 117	97.7 ± 10.1
3	3368 ± 106	91.8 ± 9.2
4	3415 ± 111	93.1 ± 9.5

The statistical results for all of the vials in Table 8 are as follows:
$\bar{C} = 94.7$
$s_{n-1} = 2.7$
$s_{\bar{c}} = 1.3 (1.4\%)$

The mean errors of each cycle of the ten vials were about 3%. This value was greatly affected by vial #5 which was roughly 20 pCi/l lower than the average for the other nine vials. The percent errors for nine of the ten vials (neglecting #5) were between 1.45 and 1.85%. The mean value for all four cycles was 94.7 with a standard error of 1.4%.

Detector Saturation

Two detector saturation experiments were performed, one for the liquid-scintillation vials and one for the canisters with desiccant. Figure 12 shows the average net corrected count rates found for each of the 13 vials exposed versus length of exposure. Radon concentrations were not found for these vials because conversion factors were not available for the majority of the exposure times. Figure 13 shows the radon concentration computed for each of the 5 canisters exposed versus length of exposure. From Figure 12 it appears that the LS vials saturated around the 24 hour exposure period. The canisters with desiccant did not appear to saturate, since radon concentrations increase for each increasing exposure length up to 7 days. This result was expected since it was seen from the EML exposures that the amount of radon adsorbed by the charcoal is greatly reduced (up to 36%) for canisters with desiccant bags.

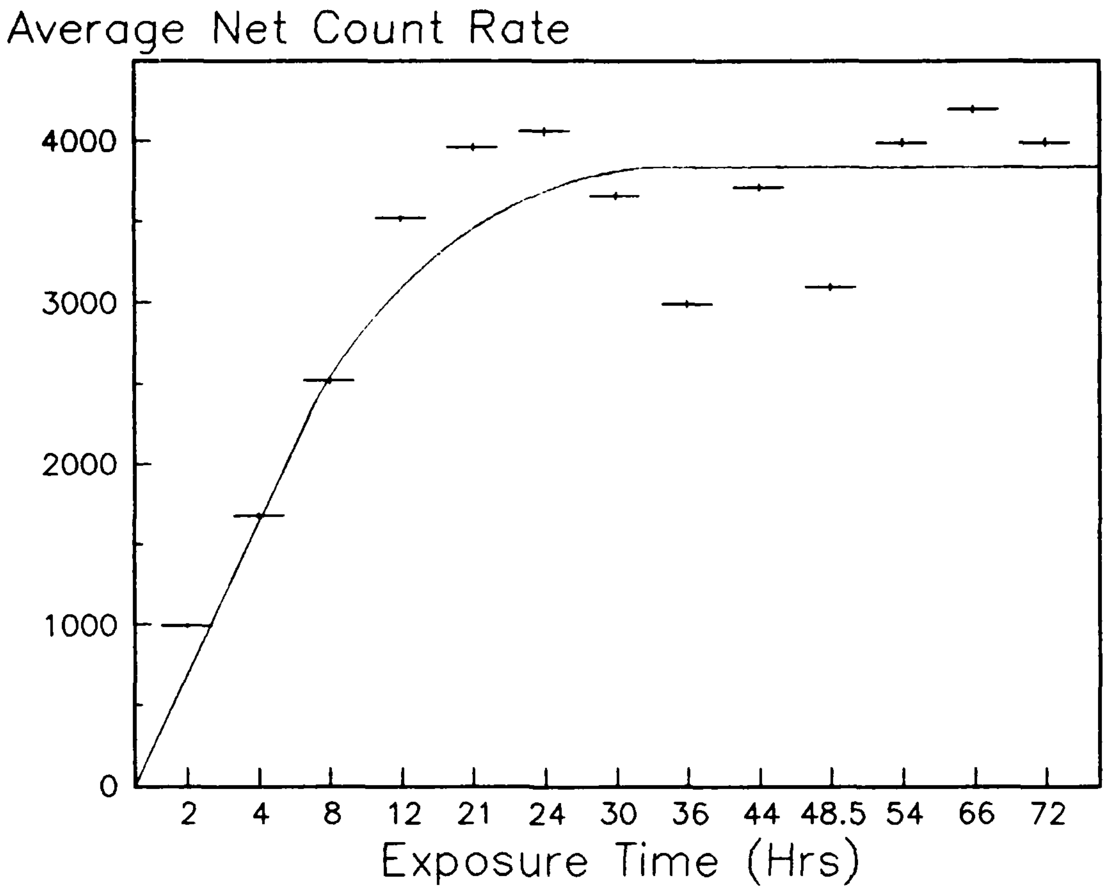

Figure 12. Vial Saturation Data for 13 Vials Exposed in the AFIT Radon Chamber

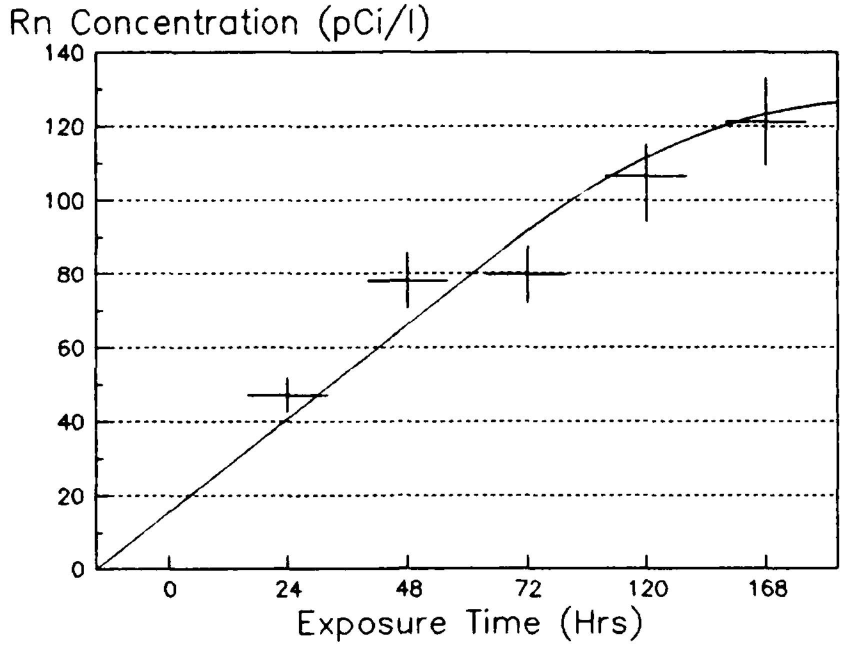

Figure 13. Can Saturation Data for 5 Cans With Desiccant Exposed in the AFIT Radon Chamber

Detector Sensitivity

The sensitivity of each type of detector was examined. Sensitivity values were determined from the EML-exposure data by converting the values of FAC to cpm per pCi/l. Sensitivity is a measure of the ability of a certain detector type to differentiate low radon concentrations from background. The values for the liquid-scintillation vials are listed in Table 9. Table 10 lists the sensitivity values for the charcoal canisters. Higher values of cpm per pCi/l indicate better detector sensitivities.

Table 9. Sensitivity Values For LS Vials

Exposure Time (Hours)	Sensitivity (cpm per pCi/l)
15.5	28.0 ± 1.5
24	32.8 ± 2.0
30.5	35.7 ± 4.3
48	38.4 ± 2.6
72	36.7 ± 5.2

The statistical results for the four exposure times from 24 hours to 72 in Table 9 are as follows:

$\bar{C} = 35.9$

$s_{n-1} = 2.4$

$s_{\bar{C}} = 1.2$

As expected, the sensitivities for the canisters with desiccant are lower than for those with no desiccant. The desiccant bags reduce the flow of air into the detector; thereby, affecting the amount of radon entering the detector. Cohen (4:461) found that adding the desiccant bags "introduced little problem with diffusion," but it appears from his article that he removed the silk screen when desiccant was placed in the detectors. Longer exposure times are required to achieve the same level of adsorption for a given radon concentration in the air being sampled.

Table 10. Sensitivity Values For Canisters

Exposure Time (Hours)	Sensitivity For Cans With Desiccant (cpm per pCi/l)	Sensitivity For Cans Without Desiccant (cpm per pCi/l)
24	5.16 ± 0.39	8.03 ± 0.56
48	9.13 ± 0.51	13.60 ± 0.73
72	11.35 ± 0.64	15.57 ± 0.89
120	14.99 ± 0.91	18.5 ± 1.7
168	14.7 ± 1.4	19.7 ± 1.3

The sensitivity values for the vials are better than those for either type of charcoal canister. This means that the vials can be used to determine lower radon concentrations. From the results in Tables 9 and 10, exposure times of 24 to 72 hours for the vials, and 5 to 7 days for canisters would be preferred.

Effect Of Desiccant Bags On Moisture Gain Of Charcoal

A comparison was done of the effect that the desiccant bags had on moisture adsorption by the charcoal in the detector. The EML canister results were used to perform this analysis. Table 11 lists the weight gain in grams for the charcoal in both types of canisters. The canisters were exposed simultaneously in pairs (two of each type) in the EML radon chamber. The charcoal in the canisters with desiccant adsorbed more moisture than the charcoal in the canisters without desiccant in almost every case. It was noted that the desiccant bags were not tightly sealed to the silk screen that covers the opening in the canister. Therefore, air was able to flow around the desiccant bags. This does not explain the curious result of increased moisture gain for the charcoal in the canisters with desiccant.

Table 11. Charcoal Moisture Gain Comparison

Exposure Time (Hours)	Canister Numbers	Charcoal Weight Gain For Cans With Desiccant (gms)	Canister Numbers	Charcoal Weight Gain For Cans Without Desiccant (gms)
24	05/08	0.17 / 0.15	025/033	0.08/0.08
48	04/010	0.20 / 0.22	023/027	0.13/0.11
72	03/09	0.26 / 0.32	029/030	0.19/0.52
120	07/06	0.20 / 0.22	028/034	0.01/0.20
168	011/012	0.35 / 0.41	037/039	0.30/0.19

Comparison of Calculated Rn Concentrations and Known Exposure Values

A pair of each of the three types of radon detectors were exposed in EML's calibrated radon chamber. The vials were sent back to our laboratory without the radon concentrations to which they were exposed to allow an unbiased assessment of the radon concentrations. The detectors were processed immediately after their return, and the results were then compared with the exposed concentrations (sent separately from the exposed detectors). LS vials were prepared per standard protocol 1 because that protocol was used to determine the calibration factors from the first EML exposure. Table 12 lists the actual radon concentration provided by EML, the average measured radon concentration and the percent error. Average values for the canisters are the mean for the two samples of each type of canister. LS vial average values are the average of the two means for the 16 counts (from 48 to 75 hours after cocktail addition) of each vial. The percent error is [(Actual - Measured) / Actual] x 100.

Table 12. Average Measured Radon Concentrations Compared to Actual Exposure Concentrations for a Blind Test (Actual Values Unknown Until Results Were Achieved)

Detector Type	Average Measured Radon Concentration (pCi/l)	Actual Radon Concentration (pCi/l)	Percent Error (%)
LS Vial	36.9 ± 2.2	38.2 ± 1.9	3.4
Can With Desiccant	41.7 ± 3.1	41.8 ± 2.1	0.24
Can Without Desiccant	45.1 ± 3.3	41.8 ± 2.1	7.9

Results from the blind test indicate that the charcoal canisters with desiccant are the detectors that best represent actual data. These detectors had only a 0.24% error from the actual concentration compared to 3.4% error for vials and 7.9% for canisters without desiccant. However, the values are derived from a sample size of two, so the reliability in the numbers is suspect.

Environmental Measurements

Environmental radon levels were measured in seven buildings on WPAFB. For this study, a canister without desiccant was exposed next to a liquid-scintillation vial to allow comparison. Where applicable, detectors were placed on different floors of the building to also allow comparison across locations within a structure. The vials were exposed for a period of two days except vials #9A and #10A, which were exposed for three days. The reason for the longer exposure was the fact that no one was in the basement of Building 20 when the vials were supposed to be sealed. All of the canisters were exposed for three days.

Table 13. Environmental Exposure Results For Detectors Exposed in Buildings on WPAFB (Areas A, C, and Kittyhawk)

Detector Location	Can #	Vial #	Radon Concentration C_i (pCi/l)
Bldg 1235 - First Floor	023	-	7.86 ± 0.24
Bldg 1235 - First Floor	-	1A	7.42 ± 0.62
Bldg 1173 - First Floor	025	-	4.78 ± 0.18
Bldg 1173 - First Floor	-	2A	5.00 ± 0.40
Medical Center - 1st Flr	027	-	0.23 ± 0.12
Medical Center - 1st Flr	-	3A	0.47 ± 0.11
Medical Center - Basement	028	-	1.41 ± 0.13
Medical Center - Basement	-	4A	0.84 ± 0.16
Bldg 825 (VOQ) - Basement	029	-	3.92 ± 0.17
Bldg 825 (VOQ) - Basement	-	5A	4.32 ± 0.49
Bldg 825 (VOQ) - First Flr	030	-	2.20 ± 0.14
Bldg 825 (VOQ) - First Flr	-	6A	2.05 ± 0.21
Bldg 826 (VOQ) - First Flr	033	-	4.67 ± 0.18
Bldg 826 (VOQ) - First Flr	-	7A	4.62 ± 0.55
Bldg 826 (VOQ) - Basement	034	-	0.97 ± 0.13
Bldg 826 (VOQ) - Basement	-	8A	1.52 ± 0.15

Table 14. Environmental Exposure Results For Detectors Exposed in Buildings on WPAFB (Area B)

Detector Location	Can #	Vial #	Radon Concentration C_i (pCi/l)
Bldg 20 - Bsmt Photo Lab	037	-	1.45 0.13
Bldg 20 - Bsmt Photo Lab	-	9A	1.17 ± 0.27
Bldg 20 - Basement	039	-	1.17 ± 0.13
Bldg 20 - Basement	-	10A	1.28 ± 0.28
Bldg 622 - Lowest Level	040	-	0.87 ± 0.13
Bldg 622 - Lowest Level	-	11A	0.87 ± 0.13
Bldg 622 - 3 Flrs Below Gnd	042	-	0.72 ± 0.13
Bldg 622 - 3 Flrs Below Gnd	-	12A	0.92 ± 0.11
Bldg 622 - 2 Flrs Below Gnd	043	-	0.78 ± 0.13
Bldg 622 - 2 Flrs Below Gnd	-	13A	0.86 ± 0.14
Bldg 622 - Ground Level	044	-	0.87 ± 0.13
Bldg 622 - Ground Level	-	14A	0.90 ± 0.14

The vials were all prepared per standard protocol 1, and the concentrations given in Table 13 for each vial are averages of five to eight counts. The concentrations for the canisters are the result of one 30-minute count each. Most of the concentrations (9 of 14 samples) for two detectors exposed side-by-side have good agreement ($<$ 10%). All of the detector-pairs that had a difference in concentration of more than 10% had concentrations at or below 1.52 pCi/l.

V. Conclusions And Recommendations

Conclusions

The objectives of this thesis were to study the response of three types of integrating-passive radon detectors and to calibrate each type of detector. Only one of the three detector types had been examined by previous students - the charcoal canisters with no desiccant. The second detector type was constructed by adding a desiccant bag to the inside of the canister opening. The third detector type was a polyethylene liquid-scintillation (LS) vial.

Since the LS vials had not been previously examined, many of the details for exposing, processing, and counting the vials had to be determined. A preferred exposure time was established, and various protocols to process and count the vials were examined. An optimum protocol was determined in which the vials were shaken gently immediately after cocktail addition, inverted, turned upright at the 24 hour point after cocktail addition, and placed in the LSC after an additional 24 hours standing at room temperature (48 hour point after cocktail addition).

The variability in the radon concentrations found for LS vials counted by the LSC was examined. The values found were very consistent; with standard errors of the mean of between one and four percent across each protocol. This study also showed that the standard protocol chosen (protocol 3) had advantages over the other methods examined.

A study of the reproducibility of the amount of radon adsorbed by vials exposed simultaneously in the AFIT radon chamber showed that there was approximately a three percent error in the average radon concentration for a cycle of the LSC. A standard error of 1.4% was found for the mean of all four cycles of the ten vials. One vial was more than 20 percent lower than the average for the other nine vials exposed at the same time. No explanation for the vast discrepancy was found.

A calibration was performed for each detector type. Conversion factors were found to convert counts or count rates to radon concentrations in pCi/l. This data was used to compute the *sensitivity of each type of* detector. The LS vials were found to be the most sensitive, followed by the canisters without desiccant. Canisters with desiccant had the worst sensitivity. One possible explanation for the fact that the vials had the best sensitivity is the fact that the LSC counts the decay products from each element in the radon decay chain (alphas and betas), while the NaI scintillator used to count the canisters counts only gammas. An explanation for the lower sensitivity of the canisters with desiccant is the reduced air flow entering the detector, thereby reducing the rate of radon entering the detector.

The saturation times for vials and canisters with desiccant were examined. LS vials became saturated after an exposure period of around 24 hours in the AFIT radon chamber (About 120 pCi/l concentration). Canisters with desiccant still showed an upward trend after seven days in the chamber.

This result was expected because of the lesser amount of charcoal in the vials (1.3 grams versus 27 grams in the canisters). The fact that the desiccant bags affect the flow of air into the canister will also increase the time to saturate. The problem with short times to saturation is that the time over which the air sample is taken is decreased. For a 24 hour exposure period, if the concentration of radon changes the detector can account for this, but changes that occur from day to day will not be accounted for. The longer the exposure period, the longer the time period of integration. However, the moisture absorption problem reduces the optimum time of counting.

Recommendations

In an effort to improve the results and allow further comparisons of the detector types, the following recommendations are suggested:

1. Expose some LS vials to known concentrations and count them repeatedly with the LSC to determine the best time after cocktail addition to count the vials.

2. Conduct studies of the effect of humidity changes on the three detector types. Expose the detectors to varying humidities while keeping exposure time and radon concentration fixed.

3. Examine the possibility of setting up a humidity controller for the radon chamber. Dr. Philip Jenkins at Mound Laboratories may have some suggestions.

4. Attach larger desiccant bags (about 2 inches X 2 inches) firmly to the lid of the canisters. The silk screen diffusion barrier can be removed when desiccant is attached. These changes should increase the sensitivity of the detector and should enable the desiccant bag to be attached more tightly.

Appendix A: Definition of Working Level

The working level (WL) is a value used to describe the radon progeny concentration in a way that reflects their biological hazard. This biological hazard comes mainly from the energy deposited in the lungs by the alpha particles emitted by ^{218}Po and ^{214}Po. The working level is the combination of radon progeny in one liter of air that upon decay will release 1.3×10^5 MeV of alpha energy. The working level is related to the concentrations of the specific radon progeny by the following formula:

$$WL = 0.00105C_1 + 0.00516C_2 + 0.00379C_3$$

where C_1, C_2, and C_3 are the concentrations of the respective radon progeny in pCi/l.

The potential alpha energy (PAE) deposited in the lung can be determined from the following equation:

$$PAE(MeV) = 1.3x10^5 xWL$$

If radon and its progeny are in secular equilibrium at 100 pCi/l, then the radon progeny concentration would be one working level (5:23).

Appendix B: Household Exposure Sheets

INSTRUCTIONS FOR USING "RADON CAN"

Generally you will receive two cans to measure the radon level at two separate regions* in your house. In our study, we wish to determine the radon level in the living quarters of your residence as well as at the source of the highest level of the radon. Thus, since radon emanates from either soil, rocks, and possibly water, place one can in the basement in the area containing either a sump or drain. Place the other can in the room occupied most by your family, for example, your family room or bedroom. Locate the cans far enough above the floor and away from windows to avoid drafts, i.e., the can should be receiving air that is representative of that which you normally breathe.

PROCEDURE

1. Place the can in the room to be monitored.

2. To start the test, remove the duct tape from the top of the can. Stick the tape on the side of the can (just to keep it safe during the measurement period). DO NOT REMOVE the black tape that holds the lid on the can.

3. Record time and date of opening. Use the space provided below.

4. Leave the can undisturbed for three days, i.e., 72 hours.

5. To end the test, cover the hole in the can with the duct tape. Make certain that the aluminum foil on the sticky side of the tape completely covers the hole and that the tape is firmly sealed to the can.

6. Record the time and date that you sealed the hole.

7. Return the can as soon as possible, preferably on the same day that the test was ended. Since the sensitivity of the measurement diminishes with the time elapsed after sealing the can, it is essential that we receive the cans no later than three days from the end of the test.

PROVIDE THE INFORMATION REQUESTED BELOW

NAME ______________________________ ADDRESS

____________________________ (incl ZIP) ____________________________

PHONE _______________________

CAN # __________ LOCATION OF CAN

____

(Room/level of house, e.g.,bedroom/2nd floor)

DATE AND HOUR OPENED ____________________
DATE AND HOUR SEALED ____________________

CAN # __________ LOCATION OF CAN

____

DATE AND HOUR OPENED ____________________
DATE AND HOUR SEALED ____________________

* When we wish to study reproducibility, this will not apply.

INSTRUCTIONS FOR USING "RADON VIAL"

Generally you will receive two vials to measure the radon level at two separate regions* in your house. In our study, we wish to determine the radon level in the living quarters of your residence as well as at the source of the highest level of the radon. Thus, since radon emanates from either soil, rocks, and possibly water, place one vial in the basement in the area containing either a sump or drain. Place the other vial in the room occupied most by your family, for example, your family room or bedroom. Locate the vials far enough above the floor and away from windows to avoid drafts, i.e., the vial should be receiving air that is representative of that which you normally breathe.

PROCEDURE

1. Place the vial in the room to be monitored.

2. To start the test, remove the cap from the vial. Keep the cap by the vial to assure that the same cap gets back on that vial.

3. Record time and date of opening. Use the space provided below.

4. Leave the vial undisturbed for three days, i.e., 72 hours.

5. To end the test, replace the cap on the vail. Make certain that the cap is securely fastened.

6. Record the time and date that you sealed the vial.

7. Return the vial as soon as possible, preferably on the same day that the test was ended. Since the sensitivity of the measurement diminishes with the time elapsed after sealing the vial, it is essential that we receive the vials no later than three days from the end of the test.

PROVIDE THE INFORMATION REQUESTED BELOW

NAME ______________________________ ADDRESS

____________________________ (incl ZIP)____________________________

PHONE _______________________

VIAL # __________ LOCATION OF VIAL

____

(Room/level of house, e.g.,bedroom/2nd floor)

DATE AND HOUR OPENED ____________________

DATE AND HOUR SEALED ____________________

VIAL # __________ LOCATION OF VIAL

____

DATE AND HOUR OPENED ____________________

DATE AND HOUR SEALED ____________________

* When we wish to study reproducibility, this will not apply.

Appendix C: RADON Program For Canisters

```
'*************************************************************** 10
'RAD3 finds Rn-222 in pCi/l from a THREE-DAY exposure of charcoal in
a can as designed by B. Cohen and calibrated by J.Bouchard, GNE 88M.
20 'The calculation uses the total gross counts/30 min. under the full-
energy peaks from gamma rays of Pb-214 and Bi-214 between 220-390
keV and 550-680 keV. The counts include background because this
program subtracts
30 'a background obtained by PERIODIC measurements with long counting
times so that the standard deviation is reduced. This requires the user
to      provide the standard deviation for the combined background when
the
40 'program asks for it at the time it requests verification of the
backgrounds in the two regions. These data, the backgrounds for the
two     regions and the standard deviation, are stored in a file named
BKG.
50 'OUTPUT OF RN 222 IN PCI/L IS TO THE SCREEN AND TO THE DISK
FILE RADON3.    MAJOR VARIABLES:
60 'C1.......Number of counts between 220-390 keV in a 30 minute count
C2.......Number of counts between 550-680 keV in a 30 minute count
B1.......Background/30 min. between 220-390 keV
70 '    B2.......Background/30 min. between 550-680 keV
BTOT.....B1 + B2, the combined backgrounds
CTOT.....C1 + C2, the combined gross count from sample
80 '    T........Time in HOURS between sealing of can at the end of the
exposure to time of starting the count. MUST BE AT LEAST THREE HOURS.
90 '    ID.......ID # of can
SIGCT....Standard deviation in net total counts, CTOT
SIGBG....Standard deviation in total background, BTOT
100 '   FAC......Calibration factor determined from can's exposure in to a
known concentration of Radon chamber at Mound Facility at known
humidity for exactly THREE days. UNITS are
110 ' (pCi/liter)/(counts/30 min.)
120 ' SIGFAC...Standard deviation in FAC as calculated from counting
cans  exposed at Mound combined with statistical uncertainty in the
radon concentration as provided by Mound.
130 ' RNCON....Radon concentration in pCi/l calculated from net
counts/30 min from the exposed can multiplied by FAC.
140 ' SIGRN....Calculated standard deviation for the Rn concentration,
RNCON
150 '*****************************************************************
160 OPEN "RN3" FOR OUTPUT AS #2
170 PRINT #2, "Can No.     Hours Since Sealed     Radon Conc. (pCi/l)
Uncertainty (pCi/l)"
180 GOSUB 380 :'***Establish Background Level***
190 INPUT "Type D to input data from disk file CANS or K to input data
from the keyboard. ",OPT$
```

```
200 IF OPT$ = "d" OR OPT$ = "D" THEN PRINT "Can No.     Hours Since
Sealed     Radon Conc. (pCi/l)     Uncertainty (pCi/l)"
210 IF OPT$ = "d" OR OPT$ = "D" THEN GOSUB  50
ELSE GOSUB 640
220 CTOT = C1 + C2
230 BTOT = B1 + B2
240 CNET = CTOT-BTOT
250 SIGCNET = SQR(CTOT + SIGBG^2)
260 RSIGC0 = SIGCNET/CNET
270 DC = (LOG(2))/(3.823*24) :'***Decay Constant for Rn-222, inverse
hrs.***'
280 C0 = CNET*EXP(T * DC) :'***Net counts corrcted for decay between
closing                                  can and start of counting***'
290 FAC = .002141 :'***pCi/liter per net corrected counts/30 min***'
300 'FAC AND ITS UNCERTAINTY SIGFAC WERE CALCULATED FROM EML
EXPOSURE DATA
310 RNCON = C0*FAC
320 RSIGFAC = 1.082E-04/.002141
330 RSIGRN = SQR(RSIGFAC^2 + RSIGC0^2)
340 SIGRN = RNCON*RSIGRN
350 PRINT USING "  ###                ###.##                ####.##
####.##      "; ID; T; RNCON; SIGRN
360 PRINT #2, USING "  ###                ###.##                ####.##
####.##      "; ID; T; RNCON; SIGRN
370 GOTO 210
380 '********************************************************************
Change Background Count Subroutine
*********************************************************************

390 OPEN "BKG" FOR INPUT AS #1
400 INPUT #1, B1,B2,SIGBG
410 CLOSE #1
420 PRINT "THE VALUES FOR B1,B2,SIGBG ARE:  ";B1,B2,SIGBG
430 INPUT "DO YOU WANT TO CHANGE THEM? (Y OR N)", ANS$
440 IF ANS$ = "n" OR ANS$="N" THEN 530
450 INPUT "ENTER  THE NEW VALUES FOR B1,B2,SIGBG:",B1,B2,SIGBG
460 PRINT "THE VALUES YOU WANT ARE AS FOLLOWS: ",B1;B2;SIGBG,"COR-
RECT?"
470 INPUT "DO YOU WANT TO CHANGE THEM? (Y OR N)", ANS$
480 IF ANS$ = "y" OR ANS$="Y" THEN 450
490 PRINT "OK, NEW VALUES OF B1,B2, AND SIGBG WILL BE STORED IN
FILE ,BKG"
500 OPEN "BKG" FOR OUTPUT AS #1
510 WRITE #1,B1,B2,SIGBG
520 CLOSE #1
530 PRINT "OK, RADON CONC. WILL BE CALCULATED WITH VALUES OF B1,
B2, AND SIGBG              NOW RESIDENT IN FILE NAMED BKG"
540 RETURN
550 '********************************************************************
Input from Disk File Subroutine
*********************************************************************
```

```
560 ON ERROR GOTO 630
570 OPEN "cans" FOR INPUT AS #3
580 IF EOF(3) THEN 610
590 INPUT #3, ID, T, C1, C2
592 PRINT "The can ID # is, ";ID,"The time lapse between close and count
is, ";T,"Gross count from 220-390 = C1= ";C1,"Gross count 550-680=C2=
";C2
600 RETURN
610 CLOSE #3
620 END
630 IF ERR = 55 THEN RESUME NEXT ELSE ON ERROR GOTO 0
640 '**********************************************************************
Input from Keyboard Subroutine
******************************************************************
650 INPUT "What is the can number? (Enter 0 to quit) ",ID
660 IF ID=0 THEN 720
670 INPUT "How long, in hours, was it between the time the can was
sealed and  the time the count was started? ",T
680 INPUT "How many 220-390 keV counts in 30 minutes ",C1
690 INPUT "How many 550-680 keV counts in 30 minutes ",C2
700 PRINT "Can No.     Hours Since Sealed     Radon Conc. (pCi/l)
Uncertainty (pCi/l)"
710 RETURN
720 CLOSE #2
730 END
```

Bibliography

1. Bodansky, David. "Overview of the Indoor Radon Problem," Indoor Radon and Its Hazards, edited by David Bodansky and others. Seattle: University of Washington Press, 1987.

2. Bouchard, Joseph P. Development of Techniques to Relate Radon Levels in Homes in the Dayton Area to Local Geology and Fill Material, MS Thesis, AFIT/GNE/ENP/88M-2. School of Engineering, Air Force Institute of Technology (AU), Wright Patterson AFB, OH, March 1988.

3. Cohen, Bernard L. and Ernest Cohen. "Theory and Practice of Radon Monitoring With Charcoal Adsorption," Health Physics, 45: 501-508 (August 1983).

4. Cohen, Bernard L. and Richard Nason. "A Diffusion Barrier Charcoal Adsorption Collector for Measuring Rn Concentrations in Indoor Air," Health Physics, 49: 457-463 (August 1985).

5. Eisenbud, Merril. Environmental Radioactivity. San Diega CA: Academic Press, 1987.

6. Frame, R. "Radon and Its Daughters," ORNL Briefing, June 1989.

7. George, Andreas C. "Passive Integrated Measurement of Indoor Radon Using Activated Carbon," Health Physics, 46: 867-872 (April 1984).

8. Gill, Charles W. Time Averaged Measurements of Household Radon Concentration Using Charcoal Adsorption," NENG 6.12 Laboratory Report, 24 September 1986.

9. Hopke, Philip K. Radon and Its Decay Products. Washington DC: American Chemical Society, 1987.

10. Knoll, Glenn F. Radiation Detection and Measurement. New York: John Wiley And Sons, 1979.

11. Little, Capt David R. Analysis of Radon and Radon Progeny in Residences: Factors That Affect Their Amounts and Methods of Reduction, MS Thesis, AFIT/GNE/ENP/85M-14. School of Engineering, Air Force Institute of Technology (AU), Wright Patterson AFB, OH, March 1985.

12. Nuclear Energy Agency. Metrology and Monitoring of Radon, Thoron and Their Daughter Products. Paris: Nuclear Energy Agency, 1985.

13. Packard Instrument Company. "Tri-Carb Liquid Scintillation Analyzers Operation Manual," Packard Instrument Company, 1988.

14. Walker, F. William and others. Chart of the Nuclides (Thirteenth Edition). San Jose CA: General Electric Company, 1984.

15. Weidner, Lt John A. Reduction of Radon Progeny in Indoor Air. MS Thesis, AFIT/GNE/ENP/86M-13. School of Engineering, Air Force Institute of Technology (AU), Wright Patterson AFB, OH, March 1986.

VITA

Captain David L. Sharp [redacted] He graduated from Warwick High School in Lititz, Pennsylvania in 1980 and attended Virginia Polytechnic Institute and State University at Blacksburg, Virginia, from which he received the degree of Bachelor of Science in Nuclear Science in June 1984. After graduation he attended the Air Force Officer Training School at Lackland AFB, Texas. Upon graduation in February 1985, he was commissioned a second lieutenant in the United States Air Force. His first assignment was as a product assurance engineer at Aeronautical Systems Division at Wright-Patterson AFB, OH where he remained until he entered the Air Force Institute of Technology School of Engineering in August 1988.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GNE/ENP/90M-6	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION School of Engineering 6b. OFFICE SYMBOL (If applicable) AFIT/ENP	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB OH 45433	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

See Block 19

12. PERSONAL AUTHOR(S)

David L. Sharp, B.S., Capt, USAF

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
MS Thesis	FROM ______ TO ______	1990 March	69

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP
18	04	
18	08	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Rare Gases, Radon, Radium Radioactivity (1) Natural Radiation, Radiation (1), Ionizing Radiation (2), Alpha Particles

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Title: Evaluation of Three Passive-Integrating Charcoal Detectors for Measuring Radon Concentrations

Thesis Chairman: George John
Associate Professor of Nuclear Physics

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. George John	22b. TELEPHONE (Include Area Code) 513-255-4498 / 22c. OFFICE SYMBOL AFIT/ENP

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

Three types of passive-integrating charcoal detectors that determine Radon-222 (Radon) concentrations in air samples were studied. Each detector type examined uses activated charcoal to adsorb radon from air samples that enter through a diffusion barrier. This results in a time-integrated sample. The three detector types analyzed were liquid-scintillation vials and canisters with and without moisture-absorbing desiccant. The LS vials contain a mixture of charcoal and desiccant.

All three types of detectors were calibrated in a chamber of known radon concentration. Since the LS vials had not previously been studied at AFIT, the optimum procedure for exposing, processing, and counting the vials was established. An automated liquid-scintillation counter (LSC) was used for determining the radon levels of the LS vials. The variability in the radon concentrations computed by the LSC for repeated counting of a single vial was examined and was found to be between 1 and 4 %. Reproducibility of radon adsorption by a group of vials exposed simultaneously was examined. Reproducibility values for a group of ten vials counted for 4 cycles had a standard error of 1.4%.

A blind test was performed where the detectors exposed to a known concentration, prepared, counted, and then the concentrations measured were compared to actual values. The measured values were within 0.2 % to about 8% of the actual concentrations. Exposure times of 24 to 48 hours ere recommended for the vials and 3 to 7 dats for the canisters.